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Method for estimating time length using simultaneous phase measurements in the system of simultaneously and independently operating generators



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Introduction. This paper is devoted to the development of a method for estimating the current time-frequency parameters of each of a set of simultaneously and independently operating generators in the radio electronic system. A general case is considered, in which the deviation of true values of the nominal generator parameters from the assumed values of these parameters is determined not only by random, but also by long-term frequency deviation. The work objective is to generalize the method for estimating the time-frequency parameters of signals (long-term nominal frequency and current frequency deviation from the nominal value) based on the simultaneous measurement of the phases of signals generated in the system of independently functioning generators. The research task is to consider a system of simultaneously and independently operating generators. Each of them generates harmonic signals, whose time-frequency parameters, such as the average frequency, are constant during a certain interval of observation. But herewith, these time-frequency parameters are known with insufficient accuracy due to the influence of external factors (changes in temperature, pressure, supply voltage, etc.). It is required to obtain estimates of the time-frequency parameters of signals (the duration of the measuring interval, values of the long-term frequency and the standard deviation) from the results of measurements of the phases of signals formed by the generators at measuring intervals belonging to the observation interval, within which the average frequency remains constant.
Materials and Methods. A system of simultaneously and independently functioning generators is considered. The long-term value of signal frequency for each of the generators over the observation interval remains constant, but it is known with some margin of error. During the observation interval, several measurements of the signal phase of each of the generators are performed. At the same time, the current values of the signal frequency and the duration of the measuring interval have random deviations from the long-term values, and follow the normal distribution law with zero mathematical expectation and a known variance. The estimation of time-frequency parameters based on the results of measuring the signal phases is carried out using a multidimensional likelihood function. The maximum is found on the base of solving the redefined system of linear algebraic equations.
Results. A new mathematical model and a numerical-analytical method for determining the time-frequency parameters of signals are developed. They take into account both the long-term constant frequency deviation and short-term random deviations.
Discussion and Conclusions. The results obtained can be used under the development and creation of data-measuring and information-telecommunication systems, including geographically distributed systems. The resulting estimates of the time-frequency parameters enable to increase the signal frequency stability and, accordingly, to improve the accuracy of measurements and the quality of information transfer.

Keywords: high-frequency generators, high frequency radio signals, statistical frequency stabilization method, frequency stability, least square method (LS method).

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Метод оценивания длительности временного интервала с использованием одновременных измерений фазы в системе одновременно и независимо работающих генераторов

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Введение. Статья посвящена разработке метода оценивания текущих частотно–временных параметров каждого из совокупности одновременно и независимо функционирующих генераторов в составе радиоэлектронной системы. Рассмотрен общий случай, при котором отклонение истинных значений номинальных параметров генераторов от предполагаемых значений указанных параметров определяется не только случайным, но и долговременным отклонением частоты. Целью работы является обобщение метода оценивания частотно–временных параметров сигналов (долговременной номинальной частоты и текущего отклонения частоты от номинального значения) на основе одновременного измерения фаз сигналов, формируемых в системе независимо функционирующих генераторов. Постановка задачи – рассматривается система из одновременно и независимо функционирующих генераторов, каждый из которых формирует гармонические сигналы, частотно–временные параметры которых, такие как средняя частота, являются в течение некоторого интервала наблюдения постоянными, но известными с недостаточной точностью из–за влияния внешних факторов (изменение температуры, давления, напряжения питания и т.д.). Требуется по результатам измерений фаз сигналов, формируемых генераторами на измерительных интервалах, принадлежащих интервалу наблюдения, в пределах которых значения средней частоты остаются постоянными, получить оценки частотно–временных параметров сигналов – длительности измерительного интервала, значений долговременной частоты и среднеквадратического отклонения частоты.

Математическая модель и методы решения. Рассматривается система одновременно и независимо функционирующих генераторов. Долговременное значение частоты сигнала для каждого из генераторов на интервале наблюдения остается постоянным, но известным с некоторой погрешностью. В течение интервала наблюдения проводится несколько измерений фазы сигналов каждого из генераторов. При этом текущие значения частоты сигнала и длительности измерительного интервала имеют случайные отклонения от долговременных значений и подчиняются нормальному закону распределения с нулевым математическим ожиданием и известной величиной дисперсии.

Оценивание частотно-временных параметров по результатам измерения фаз сигналов проводится с использованием многомерной функции правдоподобия. В качестве оценок случайного отклонения частоты сигналов и длительностей интервалов измерения, выбираются значения, доставляющие максимум функции правдоподобия. Нахождение максимума проводится на основе решения переопределенной системы линейных алгебраических уравнений.

Результаты исследования. Разработана новая математическая модель и численно–аналитический метод определения частотно–временных параметров сигналов, учитывающие как долговременное постоянное отклонение частоты, так и кратковременные отклонение, носящие случайный характер.

Обсуждение и заключения. Полученные результаты могут быть использованы при разработке и создании информационно–измерительных и информационно-телекоммуникационных систем, в том числе территориально распределенных систем. Получаемые оценки частотно-временных параметров позволяют повысить стабильность частоты сигналов и соответственно повысить точность проводимых измерений и качество передачи информации.

Ключевые слова: генераторы высокочастотных колебаний, высокочастотные радиосигналы статистический метод стабилизации частоты, стабильность частоты, метод наименьших квадратов.

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Introduction. The constant growth of requirements for audio and video information transmission, for data formation and transmission systems, necessitates an increase in stability of the time-frequency parameters of signals generating in radio-electronic systems (RES) [1]. The information-telecommunication systems and data-measuring ones are typical examples of such systems. One of the components in providing high efficiency of such systems is

associated with the formation of signals with highly stable time-frequency parameters. The latter is relevant, in particular, for the systems of information transmission with complex signals, radar and radio navigation systems, and audio and video information transmission systems as well.

Currently, the main approach in the creation of RES is a modular construction principle, which determines the use of functionally completed blocks and devices connected to each other. The application of this approach leads to presence of a large number of high-frequency signal (HF signal) generators in any radio-electronic system. At the same time, functional completeness of each of the devices included in the system enables to consider the HF-signal generators of these devices as units operating simultaneously and independently on a certain time interval.

Despite the fact that signal generators in various devices have different parameters, the presence of a large number of simultaneously and independently functioning generators in the RES provides determining the current values of the time-frequency parameters of these signals through measuring and subsequent processing of the generated signals phases[1] [2–6]. The latter makes it possible to estimate the current values of the time-frequency parameters with higher accuracy. In turn, the obtained values of the time-frequency signal parameters are associated with the parameters of the generators that are forming them. That allows either to stabilize the generators frequency, or to consider its current value during the subsequent signal processing [2–6].

Well-known solutions to the problem of estimating the current time-frequency parameters take into account, as a rule, only random components of the frequency deviation due to the influence of various factors. In this case, the values of such parameter as the nominal (mean) frequency of the generator are considered known. At the same time, in many cases, long-term frequency deviations associated with both the influence of external factors and the technology of generator production are not analyzed in the papers under examination.

Thus, the solution to the problem of estimating the time-frequency parameters of signals, such as the nominal (mean) frequency and random deviations from the average frequency of generators, is a challenge.

The paper objective is the generalization of the method of estimating the time-frequency signal parameters (the long-term nominal frequency and the current frequency deviation from the nominal value) based on the simultaneous measurement of the signal phases forming in the system of independently functioning generators.

As in the paper [3], let us consider the system of $N+1$ generators, each of which forms the harmonic signals, whose time-frequency parameters, such as average frequency ω_n, are constant, but known with insufficient accuracy due to the influence of external factors (changes in temperature, pressure, supply voltage, etc.) during a certain observation interval.

It is required to obtain estimates of the time-frequency parameters of signals (the duration of the measuring interval, frequency values and RMS (root–mean–square, or standard, deviation) of signals) from the results of measurements of the phases of the signals formed by the generators at the measuring intervals belonging to the observation interval, within which the average frequency values remain constant.

Mathematical model and solution method. For the system of $N+1$ generators under consideration, let us present the signals formed by each of the generators, as

$$s_n(t) = A_n \cos\left(\omega_n \cdot t + \varphi_n\right), \quad n = 1, ..., N+1. \tag{1}$$

Using one of the generators (hereinafter the $N+1$ generator), we will form measuring intervals of nominal duration $t_m^{(0)}$ ($m = 1, ..., M$), such that during all the specified intervals, the average frequency and RMS of the frequency of each of the generators can be considered constant.

We represent the measured values of signals phase $\Phi_{n,m}$ of each of N generators ($n = 1, ..., N$) on the *m*-th measuring interval ($m = 1, ..., M$) as follows:

$$\Phi_{n,m} = \left(\omega_n + \Delta\omega_{n,m}\right)\left(t_m^{(0)} + \Delta t_m\right), \quad n = 1, ..., N, \quad m = 1, ..., M, \tag{2}$$

where $\Delta\omega_{n,m}$ – is random deviation of the *n*-th generator frequency on the *m*-th measuring interval from the average value ω_n; $t_m^{(0)}$ and Δt_m are, respectively, nominal duration and deviation from the nominal value of the *m*-th measuring interval duration.

For the mean value frequency, taking into account the modern production technology of HF–generators, we can write

$$\omega_n = \omega_n^{(0)} + \delta\omega_n, \quad \delta\omega_n \ll \omega_n^{(0)}, \quad n = 1, ..., N+1, \tag{3}$$

where the values $\omega_n^{(0)}$ are known, and $\delta\omega_n$, with account for the influence of external factors, are unknown.

Taking into account the expressions (3), the relation (2) takes the form

[1] Gabrielyan DD, Prygunov AG, KhutortsevVV, et al. Generator frequency stabilization method. RF Patent no. 2219654, 2003. (In Russ.)

$$\Phi_{n,m} = \left(\omega_n^{(0)} + \delta\omega_n + \Delta\omega_{n,m}\right)\left(t_m^{(0)} + \Delta t_m\right),\quad n = 1,...,N,\quad m = 1,...,M. \tag{4}$$

After linearization (the terms $\delta\omega_n \cdot \Delta t_m$ and $\Delta\omega_{n,m} \cdot \Delta t_m$, are discarded), the expression (4) enables to estimate the random deviation of the frequency of the *n*-th generator on the *m*-th measurement interval as follows:

$$\Delta\omega_{n,m} = \frac{\Phi_{n,m} - \Phi_{n,m}^{(0)} - \delta\omega_n \cdot t_m^{(0)} - \omega_n^{(0)} \cdot \Delta t_m}{t_m^{(0)}},\quad n = 1,...,N,\quad m = 1,...,M, \tag{5}$$

where $\Phi_{n,m}^{(0)} = \omega_n^{(0)} \cdot t_m^{(0)}$.

The frequency deviations $\Delta\omega_{n,m}$ ($n = 1,...,N$, $m = 1,...,M$) and deviations of measurement interval duration Δt_m ($m = 1,...,M$) follow the normal distribution law [7]:

$$p\left(\Delta\omega_{n,m}\right) = \frac{1}{\sqrt{2\pi}\sigma_n^{(0)}}\exp\left[-\frac{\left(\Delta\omega_{n,m}\right)^2}{2\left(\sigma_n^{(0)} \cdot \omega_n^{(0)}\right)^2}\right],\ p\left(\Delta t_m\right) = \frac{1}{\sqrt{2\pi}\sigma_{N+1}^{(0)}}\exp\left[-\frac{\left(\Delta t_m\right)^2}{2\left(\sigma_{N+1}^{(0)} \cdot t_m^{(0)}\right)^2}\right], \tag{6}$$

where $\sigma_n^{(0)}$ are known values of the relative instability of the frequency of the *n*-th generator ($n = 1,...,N$).

The given relations describe the mathematical model of the system of generators that function simultaneously and independently.

Solution method. Taking into account the relations (5) and (6), we can write the multidimensional logarithmic likelihood function:

$$L\left(\delta\omega, \Delta \mathrm{t}\right) = -\sum_{m=1}^{M}\sum_{n=1}^{N}\left\{\ln\sqrt{2\pi} + \ln\sigma_n + \frac{\left(\Phi_{n,m} - \Phi_{n,m}^{(0)} - \delta\omega_n \cdot t_m^{(0)} - \omega_n^{(0)} \cdot \Delta t_m\right)^2}{2\left(\sigma_n^{(0)} \cdot \omega_n^{(0)} \cdot t_m^{(0)}\right)^2}\right\}, \tag{7}$$

which includes the vectors $\delta\omega$ and $\Delta \mathrm{t}$, whose elements are unknown values, respectively, $\delta\omega_n$ ($n = 1,...,N$) and Δt_m ($m = 1,...,M$).

The estimates $\delta\omega_n$ and Δt_m are found from the maximum condition (7) and correspond to the solution of the system of linear algebraic equations (SLAE).

$$\begin{cases} \dfrac{\partial L\left(\delta\omega, \Delta \mathrm{t}\right)}{\partial\delta\omega_n} = 0, & n = 1,...,N, \\ \dfrac{\partial L\left(\delta\omega, \Delta \mathrm{t}\right)}{\partial\Delta t_m} = 0, & m = 1,...,M. \end{cases} \tag{8}$$

The equations in (8) have the form

$$\begin{aligned} &\frac{\left(\Phi_{n,m} - \Phi_{n,m}^{(0)} - \delta\omega_n \cdot t_m^{(0)} - \omega_n^{(0)} \cdot \Delta t_m\right) \cdot t_m^{(0)}}{\left(\sigma_n^{(0)} \cdot \omega_n^{(0)} \cdot t_m^{(0)}\right)^2} = 0,\quad n = 1,...,N, \\ &\frac{\left(\Phi_{n,m} - \Phi_{n,m}^{(0)} - \delta\omega_n \cdot t_m^{(0)} - \omega_n^{(0)} \cdot \Delta t_m\right) \cdot \omega_n^{(0)}}{\left(\sigma_n^{(0)} \cdot \omega_n^{(0)} \cdot t_m^{(0)}\right)^2} = 0,\quad m = 1,...,M. \end{aligned} \tag{9}$$

In a matrix form, the SLAE (9) can be presented as:

$$\begin{pmatrix} \mathrm{A}_{1,1} & \mathrm{A}_{1,2} \\ \mathrm{A}_{2,1} & \mathrm{A}_{2,2} \end{pmatrix}\begin{pmatrix} \delta\omega \\ \Delta \mathrm{t} \end{pmatrix} = \begin{pmatrix} \mathrm{B}_1 \\ \mathrm{B}_2 \end{pmatrix}, \tag{10}$$

where $A_{1,1}$ is the block with dimensions $N \cdot M \times N$ with elements $a_{n\cdot m,m}^{(1,1)} = \left(\sigma_n^{(0)} \cdot \omega_n^{(0)}\right)^{-2}$; $A_{1,2}$ is the block with dimensions $N \cdot M \times M$ with elements $a_{n\cdot m,m}^{(1,2)} = \left(\sigma_n^{(0)}\right)^{-2} \cdot \left(\omega_n^{(0)} \cdot t_m^{(0)}\right)^{-1}$;

$A_{2,1}$ is the block with dimensions $N \cdot M \times N$ with elements $a_{n\cdot m,m}^{(2,1)} = \left(a_{n,m}^{(1,2)}\right)^T$;

$A_{2,2}$ is the block with dimensions $N \cdot M \times M$ with elements $a_{n\cdot m,m}^{(2,2)} = \left(\sigma_n^{(0)} \cdot t_m^{(0)}\right)^{-2}$;

B_1 is the block with dimensions $N \cdot M \times 1$ with elements $b_{n\cdot m}^{(1)} = \dfrac{\Phi_{n,m} - \Phi_{n,m}^{(0)}}{\left(\sigma_n^{(0)} \cdot \omega_n^{(0)}\right)^2 \cdot t_m^{(0)}}$;

B_2 is the block with dimensions $N \cdot M \times 1$ with elements $b_{n\cdot m}^{(2)} = \dfrac{\Phi_{n,m} - \Phi_{n,m}^{(0)}}{\left(\sigma_n^{(0)} \cdot t_m^{(0)}\right)^2 \cdot t_m^{(0)}}$;

T is the sign of the matrix transposition.

The system of equations (9) contains N of the unknown components $\delta\omega_n$ and M of the unknown elements Δt_m . The total number of measured values of signal phase is $N \cdot M$. The estimation of their values, taking into account the measurement errors, should be carried out by the least-square method (LSM) [8-10]. In this case, the condition $N \cdot M > N + M$ must be met, and the number of measurement intervals must satisfy the next condition: the number of measurements M must fulfil the condition $M > N/(N-1)$.

The representation of SLAE using the expressions (9) and (10) defines the numerical-analytical method for the problem solving. All elements of the matrix have an analytical representation. At the same time, when passing to the system of normal equations, as a rule, used in the LSM, obtaining the analytical expressions is also not difficult. However, the inversion of large-dimensional matrix can be performed only using the numerical methods [11–13].

The estimates $(\delta\omega_n)^*$ and $(\Delta t_m)^*$ obtained from the solution to the system of equations, represented by the expressions (9), allow us to determine current time-frequency parameters of the generators and signals forming by them.

Research Results. We propose a mathematical model describing a simultaneous and independent functioning of the generator system, and a numerical-analytical method for determining the time-frequency parameters of the signals with account for both the long-term constant frequency deviation and the short-term deviation of random nature. This approach enables:

— to evaluate, according to the results of measuring the phases of signals formed by simultaneously and independently functioning generators, not only random deviations in the frequency of the generated signals, and to obtain the estimates of the average long-term frequency of each of the generators;

— to exclude an instability influence of the time interval duration of measurements on the resulting estimates of the signal time-frequency parameters [14-16].

Discussion and Conclusions. The results obtained can be used under the development and creation of data-measuring and information-telecommunication systems, including the geographically distributed systems. The resulting estimates of the time-frequency parameters provide increasing the signal frequency stability and, accordingly, improving the accuracy of the measurements and the quality of information transmission.

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